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Super-massive Black Hole Demography: the Match between the Local and Accreted Mass Functions

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ABSTRACT
We have performed a detailed analysis of the local super-massive black-hole (SMBH) mass function based on both kinematic and photometric data and derived an accurate analytical fit in the range $10^6 \leqslant M_{\rm BH}/M_\odot \leqslant 5\times10^9$. We find a total SMBH mass density of $(4.2\pm1.1)\times10^5 M_\odot/{\rm Mpc}^3$, about 25% of which is contributed by SMBHs residing in bulges of late type galaxies. Exploiting up-to-date luminosity functions of hard X-ray and optically selected AGNs, we have studied the accretion history of the SMBH population. If most of the accretion happens at constant $\dot M_{\rm BH}/M_{\rm BH}$, as in the case of Eddington limited accretion and consistent with recent observational estimates, the local SMBH mass function is fully accounted for by mass accreted by X-ray selected AGNs, with bolometric corrections indicated by current observations and a standard mass-to-light conversion efficiency $\epsilon \simeq 10\%$. The analysis of the accretion history highlights that the most massive BHs (associated to bright optical QSOs) accreted their mass faster and at higher redshifts (typically at $z > 1.5$), while the lower mass BHs responsible for most of the hard X-ray background have mostly grown at $z < 1.5$. The accreted mass function matches the local SMBH mass function if, during the main accretion phases, $\epsilon \simeq 0.09\,(+0.04,-0.03)$ and the Eddington ratio $\lambda = L/L_{\rm Edd} \simeq 0.3\,(+0.3,-0.1)$ (68% confidence errors). The visibility time, during which AGNs are luminous enough to be detected by the currently available X-ray surveys, ranges from $\simeq 0.1\,$Gyr for present day BH masses $M^0_{\rm BH} \simeq 10^6\,M_\odot$ to $\simeq 0.3\,$Gyr for $M^0_{\rm BH} \geqslant 10^9\,M_\odot$. The mass accreted during luminous phases is $\geqslant$ 25–30% even if we assume extreme values of ϵ ($\epsilon \simeq 0.3-0.4$). An unlikely fine tuning of the parameters would be required to account for the local SMBH mass function accomodating a dominant contribution from 'dark' BH growth (due, e.g., to BH coalescence).

Key words: black hole physics – galaxies: active – galaxies: nuclei – galaxies: evolution – quasars: accretion – cosmology: miscellaneous

1 INTRODUCTION

The paradigm that quasars and, more generally, Active Galactic Nuclei (AGNs) are powered by mass accretion onto a super-massive black hole (SMBH) proposed long ago (Salpeter 1964; Zeldovich & Novikov 1969; Lynden–Bell 1969) has got very strong support from spectroscopic and photometric studies of the stellar and gas dynamics in the very central regions of local spheroidal galaxies and prominent bulges. These studies established that in most, if not all, galaxies observed with high enough sensitivity a central massive dark object (MDO) is present with a well defined relationship between the MDO mass and the mass or the velocity dispersion of the host galaxy spheroidal component (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Kormendy 2003). Although there is no direct evidence that all MDOs are black holes (BHs), the evidence for a singularity is actually very tight in the Galaxy (Schödel et al. 2002; Ghez et al. 2003) and alternative explanations are severely constrained in NGC 4258 (Miyoshi et al. 1995; see also e.g. Kormendy 2003).

Soltan (1982) showed that, in the framework of the above paradigm, the total accreted mass density can be inferred from the observed QSO/AGN counts. The basic ingredients of the calculation are *i)* the bolometric correction $k_{\rm bol}$, *ii)* the effective redshift and the corresponding K-correction, and *iii)* the mass to radiation conversion efficiency ϵ. When more precise luminosity functions of QSO/AGN became available, Chokshi & Turner (1992) presented a first esti-

mate of the accreted mass density and derived constraints on the corresponding mass function (MF). Small & Blandford (1992) tried to relate the luminosity function (LF) of optically selected AGNs to the local SMBH MF in galaxies for several possible accretion histories. Salucci et al. (1999) showed that the LF of the galaxy spheroids (encompassing E and S0 galaxies, and bulges of spiral galaxies) combined with the relationship between the spheroid and the central MDO mass allows an accurate evaluation of the local MF of the SMBHs. They concluded that the distribution of the mass that fuelled the nuclear activity, as traced by the LFs of QSOs and of AGNs contributing the X-ray background, matches the local SMBH MF, provided that $\epsilon \simeq 0.1$ and the ratio of bolometric to Eddington luminosity $\lambda = L_{\rm bol}/L_{\rm Edd}$ declines with luminosity and/or look-back time. It was also shown that the high mass tail of the local MF is due to the remnants of the bright optically selected QSOs, while at low masses the remnants of the AGNs producing most of the X-ray background largely dominate.

Recent estimates of the local MF also exploited the relationship between SMBH mass and velocity dispersion of the host spheroid (see e.g. Yu & Tremaine 2002; Aller & Richstone 2002; McLure & Dunlop 2003; Marconi et al. 2004), to reach, however, somewhat discrepant conclusions.

The aim of this paper is to compare the local MF of SMBHs with the MF of the mass accreted during the nuclear activity (AMF), in order to shed light on important open questions such as:

- is there room for a significant 'dark' accretion[1]? In particular, can BH merging be the main process building the present day SMBH MF?
- how do the X-ray and optical views of BH mass build-up compare?
- what is the typical Eddington ratio of AGNs when they accrete most of their mass?
- how long does the visible phase of the AGNs last?
- do we really need a mass-to-radiation conversion efficiency higher than the standard value of $\epsilon \simeq 0.1$, as recently argued (see e.g. Elvis, Risaliti & Zamorani 2002)?

The local SMBH MF, including the contribution from the spheroidal components of late-type galaxies, is re-estimated exploiting and extending the technique outlined by Salucci et al. (1999) and recently presented by Shankar et al. (2003). The accreted MF will be derived using up-to-date LFs as a function of cosmic time for optically and X-ray selected AGNs.

The paper is organized as follows. In Section 2 we critically discuss the relationships among luminosity, mass, and velocity dispersion of the spheroidal components of galaxies ($L_{\rm sph}$, $M_{\rm sph}$, and σ), and $M_{\rm BH}$. In Section 3 we present and discuss two estimates (derived via the velocity dispersion distribution function (VDF) and the LF, respectively) of the local SMBH MF. In Section 4 the accreted mass density is estimated. In Section 5 the accreted mass function (AMF) is computed and compared with the local MF of SMBHs. The accretion history and the AGN visibility times are analyzed in Section 6. A discussion of the results and the conclusions are presented in Section 7.

The standard flat ΛCDM cosmological model has been used, with $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

[1] By 'dark' accretion we mean accretion not traced by either optical or X-ray surveys. This is quite different from the often used term of "obscured" accretion, which is referred to accretion on type 2 AGNs (see e.g. Fabian 2003).

2 CORRELATIONS AMONG SMBH MASS, GALAXY LUMINOSITY AND VELOCITY DISPERSION

The SMBHs MF can be derived coupling the statistical information on local LFs of galaxies with relationships among luminosity (or related quantities, such as stellar mass and velocity dispersion) and the central BH mass (see e.g. Salucci et al. 1999).

Since the BH mass correlates with luminosity and velocity dispersion of the bulge stellar population, we need separate LFs for different morphological types (which have different bulge to total luminosity ratios), and it is convenient to use galaxy LFs derived in bands *as red as possible*, where the old bulge stellar populations are more prominent.

2.1 Bulge luminosity versus black hole mass

McLure & Dunlop (2002) analyzing a sample of 72 active and 20 inactive galaxies found that the central BH mass and the total R-band magnitude, M_R, of the bulge are strictly related. In particular, considering only inactive elliptical galaxies with accurate measurements of BH mass, the relation, converted to $H_0 = 70$, reads

$$\log(\frac{M_{\rm BH}}{M_\odot}) = -0.50(\pm0.05)M_R - 2.69(\pm1.04)\ , \qquad (1)$$

with a scatter of $\Delta\log(M_{\rm BH}) = 0.33$. It is worth noticing that the relationship has been derived using B-band magnitudes, translated to R-band assuming an average color (B-R)=1.57. A larger scatter $\Delta\log(M_{\rm BH}) \simeq 0.45$ was found by Kormendy & Gebhardt (2001), who used a sample including also lenticular and spiral galaxies.

For galaxies observed with a spatial resolution high enough to resolve the BH sphere of influence, Marconi & Hunt (2003) report a tight relation between the SMBH mass and the host galaxy bulge K-band luminosity

$$\log(\frac{M_{\rm BH}}{M_\odot}) = 1.13(\pm0.12)[\log(\frac{L_K}{L_{K_\odot}})-10.9]+8.21(\pm0.07) \qquad (2)$$

with a scatter $\Delta\log M_{\rm BH} = 0.31$. Translating Eq. (1) to the K-band using the colour $R-K = 2.6$ (Kochanek et al. 2001, with $K - K_{20} = -0.2$) as discussed in Sect. 3.1, it is apparent that the Marconi & Hunt (2003) relationship yields higher BH masses at fixed luminosity. Correspondingly, the derived SMBH mass density is up to a factor of 2 higher than obtained from Eq. (1). A closer analysis shows that most of the discrepancy is due to SMBH in spiral galaxies and can be ascribed to the uncertainty in the evaluation of their bulge component. Since most of the local mass density is contributed by BHs in E and S0 galaxies, we decided to exploit the relationship reported in Eq. (1).

As pointed out by McLure & Dunlop (2002), their $M_R-\log M_{\rm BH}$ relation is compatible with a linear relation between BH and spheroidal mass, $M_{\rm sph}$. Indeed, inserting the result

found by Borriello et al. (2003), $M_{\rm sph}/L_R \propto L_R^{0.21\pm0.03}$, we get $M_{\rm BH} \propto M_{\rm sph}^{1.03\pm0.12}$.

2.2 Velocity dispersion versus BH mass

While the presence of a strong correlation between BH mass and velocity dispersion of the stellar spheroid, $M_{\rm BH}-\sigma$, is undisputed (Ferrarese & Merritt 2000; Gebhardt et al. 2000), the value of its slope is still debated. A detailed analysis of the available data by Tremaine et al. (2002) yields

$$\log(M_{\rm BH}\frac{80}{H_0}) = 4.02(\pm0.32)\log(\sigma_{200}) + 8.13(\pm0.06)\ , \quad (3)$$

σ_{200} being the line-of-sight velocity dispersion in units of $200\,{\rm km\,s^{-1}}$. The slope is in reasonable agreement with the findings of Ferrarese (2002), $M_{\rm BH} \propto \sigma^{4.58\pm0.52}$. It should also be noted that the velocity dispersions used by Tremaine et al. (2002) refer to a slit aperture $2r_e$, while those reported by Ferrarese refer to $r_e/8$. The scatter around the mean relationship is small, $\Delta \log M_{\rm BH} = 0.3$, possibly consistent with pure measurement errors.

The low mass and low velocity dispersion regime is quite difficult to investigate. The analysis of M33 by Gebhardt et al. (2001) yields an upper limit on the BH mass ($\sim 1500 M_\odot$) more than 10 times below the central value predicted by Eq. (3). However the larger upper limit ($\sim 3000 M_\odot$) claimed by Merritt, Ferrarese & Joseph (2001) is consistent with the steeper $M_{BH}-\sigma$ relation found by Ferrarese (2002). Filippenko & Ho's (2003) estimate of the mass of the central BH in the least luminous type 1 Seyfert galaxy known, NGC 4395, ($M_{\rm BH} \simeq 10^4$– $10^5\,M_\odot$) is not inconsistent with Eq. (3). However it should be also mentioned that the BH mass in this case has been estimated using indirect, rather than dynamical arguments. The efforts to detect the so called intermediate mass BHs ($10^3\,M_\odot \lesssim M_{\rm BH} \lesssim 10^6\,M_\odot$) in galactic centers and therefore to constrain the very low σ ($< 50\,{\rm km\,s^{-1}}$) end of the $M_{\rm BH}$–σ relation have been recently reviewed by van der Marel (2003).

It is worth noticing that the $M_{\rm BH}$–σ relationship needs not to keep a power-law shape down to low $M_{\rm BH}$ or σ values. On the contrary, Granato et al. (2004) presented a model for the coevolution of QSOs and their spheroidal hosts whereby, in the least massive bulges, the BH growth is increasingly slowed down by supernova heating of the interstellar medium as the bulge mass (hence σ) decreases. As a result, $M_{\rm BH}$ is expected to fall steeply with decreasing σ, for $\log[\sigma({\rm km\,s^{-1}})] \lesssim 2.1$. This model also predicts that the observed spread around the mean relationship is a natural one, deriving mainly from the different virialization redshifts of host halos.

3 THE LOCAL SMBH MASS FUNCTION

The local SMBH MF can be estimated either from the local LF or from the local velocity dispersion function (VDF) of spheroidal galaxies and galaxy bulges, through the $M_{\rm BH}$–$L_{\rm sph}$ or the $M_{\rm BH}$–σ relation, respectively. Previous studies (Yu & Tremaine 2002; Aller & Richstone 2002) have shown that the two methods may yield estimates of the local mass density of SMBHs differing by a factor of $\simeq 2$. On the other hand Ferrarese (2002), McLure & Dunlop (2003) and Marconi et al. (2004) found very good agreement among the results of the two methods.

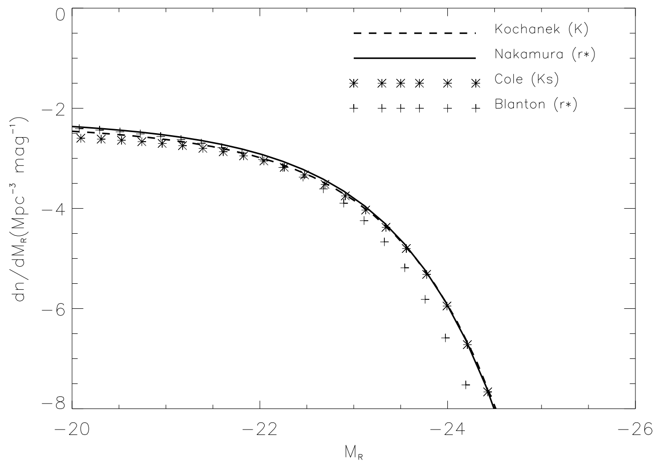

Figure 1. Galaxy luminosity function estimates converted to R-band total magnitudes as described in the text.

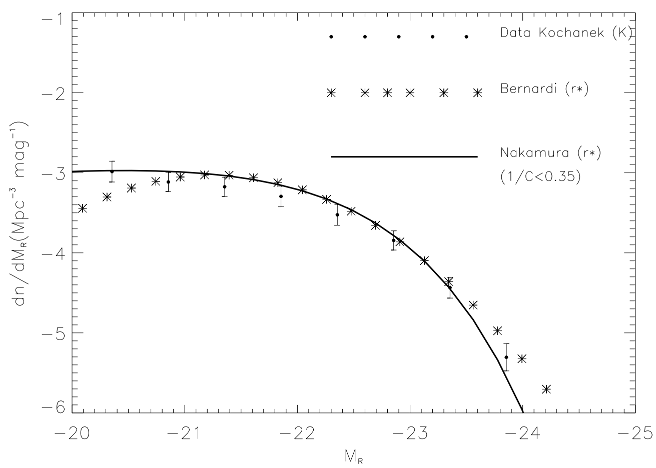

Figure 2. R-band luminosity function estimates for early-type galaxies. Data points from Kochanek et al. (2001).

3.1 Local luminosity functions of spheroids and bulges

The LFs best suited for our purpose are those in red and IR bands, which are more directly linked to the mass in old stars. Moreover, we need separate LFs for the various morphological types with different bulge to total luminosity ratios. We will use the K-band LF by Kochanek et al. (2001), the K_s-band LF by Cole et al. (2001), the r^* band LF by Blanton et al. (2001, 2003), Nakamura et al. (2002), and Bernardi et al. (2003). To compare LFs defined in different bands we must set up a common definition of the total magnitude/luminosity and of average colours.

Since we are interested in the total luminosity of

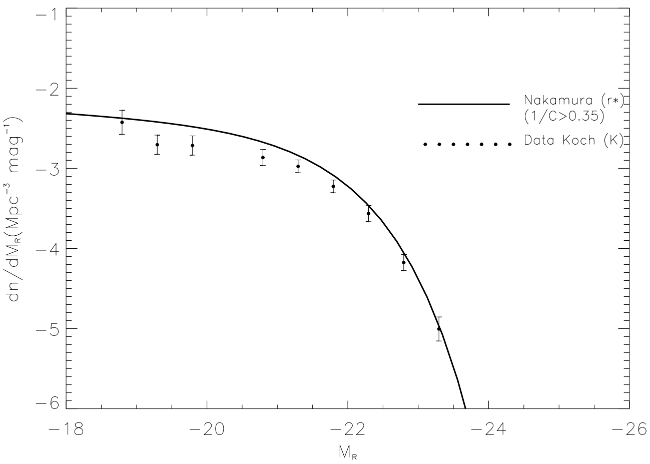

Figure 3. R-band local luminosity functions estimates for late-type galaxies.

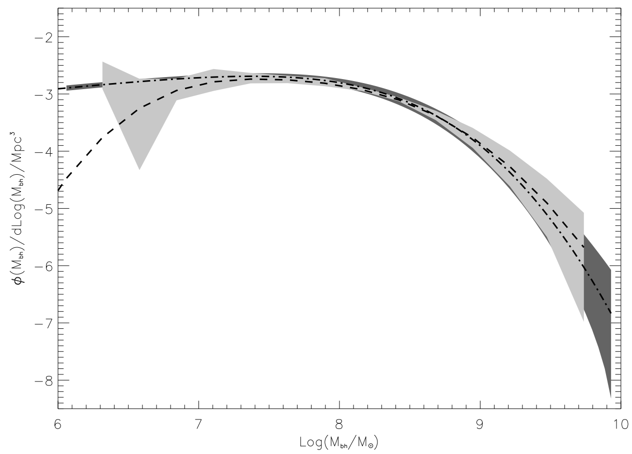

Figure 4. Local mass function of SMBHs hosted by early-type galaxies. The dot-dashed line shows the estimate obtained from the r^*-band LF (Nakamura et al. 2002) coupled with the $M_{\rm BH}$–$L_{\rm bulge}$ relation (see text); the dark gray area shows the estimated errors. The dashed line and light gray area refer the MF derived using the bivariate dispersion velocity distribution (cfr. Fig. 7).

spheroidal components of galaxies, we adopt as total magnitudes those obtained with a de Vaucouleurs profile. We have therefore corrected by -0.2 the surface brightness limited magnitudes, K_{20}, of the 2MASS sample and the Petrosian magnitudes, used by Blanton et al. (2001; 2003) and by Nakamura et al. (2002). Both magnitude systems in fact are defined for apertures which contain $\sim 80\%$ of the total flux for the adopted profile. For the Kron magnitudes of Cole et al. (2001), in the K_s band, we used a brightening of -0.11, which is required to convert them to an $r^{1/4}$ luminosity profile.

Magnitudes were converted to the R-band using the mean colours $R - K_s = 2.51$ and $R - r^\star = -0.11$ (Blanton et al. 2001). We assume an error of 0.1 mag. on colours and include it in our estimate of the final errors on the SMBH MF.

As illustrated by Fig. 1, the different estimates of the LF are in very good agreement with each other, except for that by Blanton et al. (2003), which is low at bright magnitudes (by a factor $\simeq 4$ at $M_R < -24$). Indeed the Schechter function adopted by the latter authors falls below their own data points at $M_{r^*} - 5\log(H_0/100) = -23$ (cfr. their Fig. 5). The classification by Kochanek et al. (2001) allows a clear cut distinction between early and late type galaxies. A similar classification has also been proposed by Nakamura et al. (2002). Figures 2 and 3 show that the agreement is quite satisfactory also for early and late types separately, although the early-type LF by Bernardi et al. (2003) misses objects fainter than $M_R \simeq -21$ because of their velocity dispersion criterion ($\sigma > 70\,{\rm km\,s^{-1}}$ and $S/N > 10$).

3.2 From the local luminosity function to the SMBH mass function

Based on Table 1 of Fukugita, Hogan & Peebles (1998), to obtain the LF of the spheroidal components we adopt the average R-band bulge-to-total luminosity ratios $f_{\rm sph}^{\rm early} = 0.85 \pm 0.05$ for early-type galaxies and $f_{\rm sph}^{\rm late} = 0.30 \pm 0.05$ for late-type galaxies.

The SMBH mass function was then computed convolving the LF with the $M_{\rm BH}$–$L_{\rm sph}$ relation by McLure & Dunlop (2002) [see Eq. (1)], assuming a Gaussian distribution around the mean with a dispersion $\Delta\log(M_{\rm BH}) = 0.33^{+0.07}_{-0.05}$. These uncertainties encompass most of the values quoted in the recent literature (see Sect. 2.2). The errors on the SMBH MF include the overall uncertainties on the LF, on the bulge fractions, on the $M_{\rm BH}$–$L_{\rm sph}$ relation and its scatter. The uncertainties on the LF, including those on colours, contribute about 70% of the error budget.

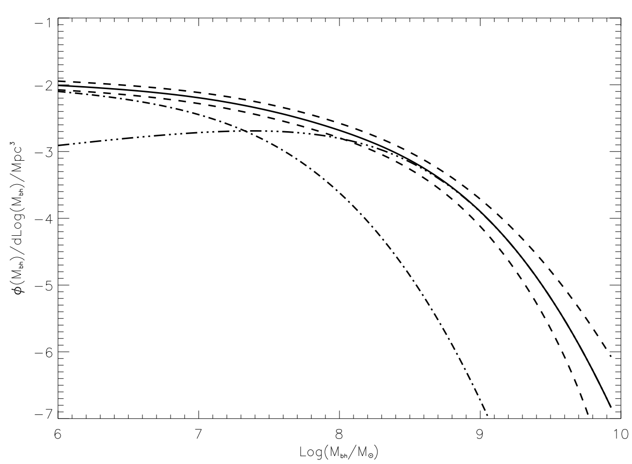

Figure 5. Global SMBH mass function (solid line) and its uncertainties (dashed lines). The three dots-dashed and the dot-dashed lines show the contributions from SMBHs hosted by early- and late-type galaxies, respectively.

The SMBH MF in early type galaxies, shown in Fig. 4, has been estimated using the LF of Nakamura et al. (2002), converted to R-band, and Eq. (1). The match with the MF computed via the VDF and the $M_{\rm BH}$–σ relation (see be-

Table 1. Local SMBH mass densities

Method	$\rho^0_{\rm BH}(10^5 M_\odot {\rm Mpc}^{-3} h^2_{70})$
Early Type Galaxies	
r^*+$M_{\rm BH} - L_{\rm bulge}$	$3.1^{+0.9}_{-0.8}$
bivariate VDF + ($M_{\rm BH}$–σ)	$3.0^{+1.0}_{-0.6}$
Sheth VDF + ($M_{\rm BH}$–σ)	2.8
Late Type Galaxies	
r^* + ($M_{\rm BH}$–$L_{\rm bulge}$)	1.1 ± 0.5

low) is very good. The corresponding SMBH mass density amounts to $\rho^0_{\rm BH}(E) = 3.1^{+0.9}_{-0.8} \times 10^5 M_\odot/{\rm Mpc}^3$, in excellent agreement with the findings of McLure & Dunlop (2003) and Marconi et al. (2004), and 30% higher than the estimate by Yu & Tremaine (2002) and Aller & Richstone (2002).

The MF of SMBH hosted by spiral bulges was computed in the same way, using the LF for late-type galaxies by Nakamura et al. (2002). Their local mass density is $\rho^0_{\rm BH}(Sp) = (1.1 \pm 0.5) \times 10^5 M_\odot/{\rm Mpc}^3$, bringing the overall mass density to $\rho^0_{\rm BH} = (4.2 \pm 1.1) \times 10^5 M_\odot/{\rm Mpc}^3$. The local number density of SMBHs with $M_{\rm BH} > 10^7 M_\odot$ is $n_{\rm SMBH} \simeq (1.3 \pm 0.25) \times 10^{-2}$ Mpc^{-3}. As illustrated by Fig. 5 the main contribution to the global mass density comes from the range $2 \times 10^7 < M_{\rm BH} < 1 \times 10^9 M_\odot$, mostly populated by SMBH in early-type galaxies, while less massive BHs are preferentially hosted in late type objects.

Our determination is very close to the result by Marconi et al. (2004), who used a methodology similar to ours. As suggested by Aller & Richstone (2002) the MF can be well represented by a four parameter function, which for our determination (per unit $d\log M_{\rm BH}$) takes the form:

$$\Phi(M_{\rm BH}) = \Phi_* \left(\frac{M_{\rm BH}}{M_*}\right)^{\alpha+1} \exp\left[-\left(\frac{M_{\rm BH}}{M_*}\right)^{\beta}\right], \quad (4)$$

with $\Phi_* = 7.7(\pm0.3) \cdot 10^{-3}$ Mpc^{-3}, $M_* = 6.4(\pm1.1) \cdot 10^7$ $M_\odot$, $\alpha = -1.11(\pm0.02)$ and $\beta = 0.49(\pm0.02)$ ($H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$). The formula holds in the range $10^6 \leqslant M_{\rm BH}/M_\odot \leqslant 5 \times 10^9$.

3.3 The local velocity dispersion function

The local VDF can be derived from the local galaxy LF exploiting the luminosity–σ relation (Gonzalez et al. 2000; Sheth et al. 2003), well established for spheroidal galaxies (Faber & Jackson 1976). The analysis of a sample of 86 nearby E and S0 galaxies, yields (de Vaucouleurs & Olson 1982; Gonzalez et al. 2000):

$$M_{B_T} = (-19.71 \pm 0.08) - (7.7 \pm 0.7)\log\sigma_{200} + 5\log h, \quad (5)$$

with $h = H_0/100\,{\rm km\,s^{-1}\,Mpc^{-1}}$. However, data for larger samples suggest a steeper relation. Bernardi et al. (2003), using about 9000 early type galaxies selected from the Sloan Digital Sky Survey (SDSS), found $L_{r^*} \propto \sigma^{3.91}$, where σ refers to a $r_e/8$ aperture. The VDF of the SDSS has been actually obtained with a fixed aperture of 1.″5 and then converted to the $r_e/8$ aperture following the conversion suggested by Jørgensen, Franx & Kjaergaard (1995).

Estimates of the local VDF have been derived by Shimasaku (1993) and Gonzalez et al. (2000) (see Kochanek 2001 for a comprehensive review), and more recently, by Sheth et al. (2003) who were the first to allow for the distribution (assumed Gaussian with a luminosity dependent width) of data points around the best fit relationship.

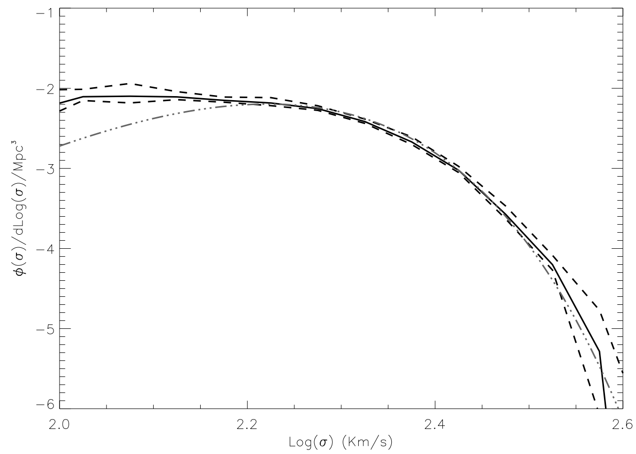

Figure 6. Velocity dispersion function. The solid line is the estimate obtained from the Nakamura et al. (2002) LF coupled with the bivariate (luminosity, σ) distribution derived from the SDSS data in the r^*-band; its uncertainty region is shown by the dashed lines. The three dots-dashed line is the estimate by Sheth et al. (2003).

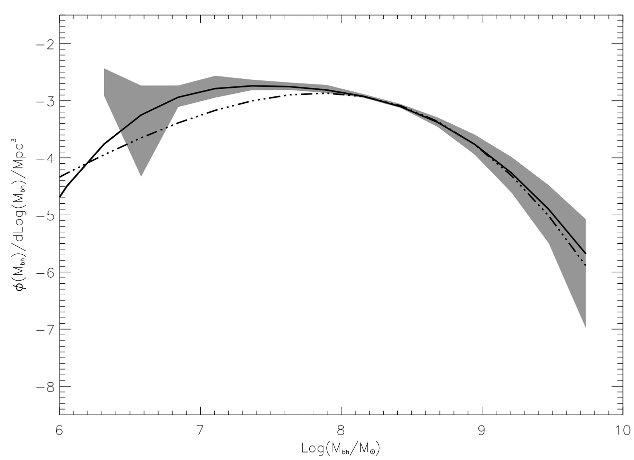

Figure 7. Estimates of the local mass function of SMBH hosted by early type galaxies, derived from the velocity dispersion functions in Fig. 6 coupled with the $M_{\rm BH}$–σ relation by Tremaine et al. (2002). The gray area represents the uncertainties on the estimate based on the bivariate (luminosity, σ) distribution.

To make a fuller exploitation of the data by Bernardi et al. (2003) we have used them to derive the bivariate distribution $p_{ij} = p(L_i, \sigma_j)$, yielding the fraction of objects in the r^*-luminosity bin centered at L_i and in velocity dispersion bin centered at σ_j. The 9000 objects in the samples, covering an absolute magnitude range $-18 \leqslant M_{r^*} \leqslant -27$ and a velocity dispersion range $1.8 \leqslant \log(\sigma) \leqslant 2.7$ (σ in km/s), have been subdivided in bins of width 0.05 both in M_{r^*} (19

bins) and in $\log(\sigma)$ (170 bins). The VDF is then estimated as:

$$n(\sigma_j) = \sum_i p_{ij} n_i, \qquad (6)$$

$n_i = n(L_i)$ being the r^*-band LF for early type galaxies by Nakamura et al. (2002; Fig. 2). The resulting VDF is shown in Fig. 6 with its errors, computed using the formula for the propagation of errors in a multivariate function with independent random errors in each variable. The uncertainties are bigger towards the two extremes, where the number of sampled objects decreases, and smaller around the knee of the function. We have checked that our results are independent of the bin size.

Using the K-band LF (Kochanek et al. 2001) converted to the r^*-band adopting a colour $K - r^* = -2.73$, appropriate for early-type galaxies (Blanton et al. 2001; Kochanek et al. 2001) we find differences in the VDF of at most 0.15 dex. From Fig. 6 it is apparent that our estimate is very close to that by Sheth et al. (2003), apart for the more rapid decline at low velocity dispersions, due to the selection criteria adopted by Bernardi et al. (2003), as noted above.

The contribution from late type galaxy bulges to the VDF is rather difficult to assess. In fact, the bulge-to-disk mass ratios depend more on morphology than on luminosity and on rotational velocity. Although for a given morphological type a correlation between the bulge velocity dispersion and the maximum rotational velocity may be expected, the use of the Tully-Fisher relation (among luminosity and rotation velocity) to infer the velocity dispersion is rather unsafe (see discussions of Sheth et al. 2003 and Ferrarese 2002).

3.4 From the VDF to the SMBH MF

In order to get an estimate of the local mass function of SMBHs, the local VDF for early-type galaxies can be convolved with the $M_{\rm BH}$–σ relation of Tremaine et al. (2002). The SDSS velocity dispersions (Bernardi et al. 2003) given for an aperture of $r_e/8$, have been converted to $2r_e$ aperture using Eq. (16) of Tremaine et al. (2002), while the $M_{BH} - \sigma$ relation of Tremaine et al (2002) has been estimated with velocity dispersions taken within an aperture corresponding to $2r_e$. We assume a Gaussian distribution of BH masses at constant σ, with a dispersion $\Delta = 0.30^{+0.07}_{-0.03}$ dex.

The SMBH MF estimates derived from the VDF obtained through the bivariate probability distribution and from the VDF by Sheth et al. (2003) are shown in Fig. 7. The shaded area shows the uncertainties on the former estimate, including the contributions from errors on both the VDF and Δ. Again, the decline for $M_{\rm BH} \leqslant 10^7\, M_\odot$ is due to the incompleteness of the SDSS sample at low velocity dispersions. The integrated mass density of SMBH in early-type galaxies is $\rho^0_{\rm BH} = 2.8 \times 10^5 M_\odot/{\rm Mpc}^3$ or $\rho^0_{\rm BH} = 3.0^{+1.0}_{-0.6} \times 10^5 M_\odot/{\rm Mpc}^3$ if we use the VDF by Sheth et al. (2003) or that obtained through the bivariate probability function, respectively. As noted above, the evaluation of the contribution of SMBHs hosted by late-type galaxies through this method is hampered by the poor knowledge of the local VDF for their bulges. Adopting the temptative estimate by Sheth et al. (2003) for the late type galaxy contribution to the VDF, coupled with Eq. (3), with the same scatter $\Delta = 0.3$, we get $\rho^0_{BH} = 1.2 \times 10^5\ M_\odot/{\rm Mpc}^3$, nicely consistent with the estimate derived from the LF.

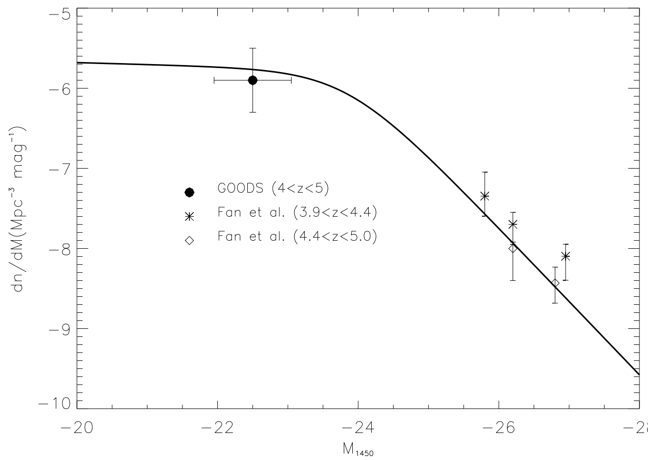

Figure 8. Optical AGN LF at high-z. Data from the SDSS (Fan et al. 2001) and GOODS survey (Cristiani et al. 2004). The solid line shows the Croom et al. (2003) power-law model at $z = 4.5$.

Wyithe & Loeb (2003) obtained a lower estimate of the total mass density mainly because they neglected the scatter Δ of the $M_{BH} - \sigma$ relationship.

4 THE ACCRETED MASS DENSITY

Soltan (1982) showed that the total mass density accumulated by accretion on BHs powering QSOs can be deduced from QSO counts, under quite simple assumptions. If ϵ is the mass to radiation conversion efficiency, the bolometric luminosity is

$$L_{\rm bol} = \epsilon \dot{M}_{\rm acc} c^2 \qquad (7)$$

and the mass accretion rate reads

$$\dot{M}_{\rm BH} = (1-\epsilon)\dot{M}_{\rm acc}. \qquad (8)$$

The conversion of luminosities measured in a given band to bolometric luminosities requires the knowledge of bolometric corrections $k_{\rm bol}$ (see, e.g., Elvis et al 1994), which may depend on luminosity and/or redshift. The mass accreted up to the present time by all AGNs brighter than L can be written as

$$\rho_{\rm acc}(>L) = \frac{1-\epsilon}{\epsilon c^2}\int_0^{z_{\rm max}} dz \frac{dt}{dz} \int_L^{L_{\rm max}} dL' k_{\rm bol}(L',z) n(L',z) L'. \quad (9)$$

where $n(L', z)$ is the *comoving* luminosity function. As noted by Soltan (1982), $\rho_{\rm acc}$ is independent of H_0 and of the QSO lifetime.

The most complete AGN surveys are those at X-ray (hard and soft), optical, and radio wavelengths. The latter selection is however rather inefficient, since only $\sim 10\%$ of AGNs are radio loud.

4.1 Mass accreted on optically selected QSOs

The 2dF survey (Boyle 2000; Croom et al. 2003) has provided an accurate determination of the redshift-dependent

LF of optically selected AGNs with $M_B < -22.5$ and $z < 2.2$. Croom et al. (2003) showed that the data are consistent with pure luminosity evolution of the form $L_B(z) = L_B(0) \times 10^{0.21z(5.476-z)}$ (for a ΛCDM model with $\Omega_m = 0.3$), peaking at $z_p \simeq 2.74$ and exponentially declining at higher redshifts. Although the luminosity function is poorly known for $z > 2.4$, there is strong evidence (see Fan et al. 2001 and Osmer 2003 for a recent review), for a rapid decrease with increasing redshift of the space density of bright QSO for $z \geqslant 3$. More recently, very deep X-ray (Barger et al. 2003) and optical (Cristiani et al. 2004) surveys have provided strong constraints on the space density of less luminous QSOs at high redshift. As illustrated by Fig. 8, the Croom et al. (2003) power-law model provides a sufficiently accurate description also of the data at $z \geqslant 4$.

Inserting such model in Eq. (9), and integrating it up to $z = 6$, we get, for $k_{\rm bol}^B = 11.8$, appropriate for $L_B = (L_\nu \nu)_B$ with $\nu_B = 6.8 \times 10^{14}$ Hz (Elvis et al. 1994) and $\epsilon = 0.1$:

$$\rho_{\rm acc}^{\rm opt} = 1.4 \times 10^5 \frac{k_{\rm bol}}{11.8} M_\odot/{\rm Mpc}^3 \ . \tag{10}$$

with objects at $z \leqslant 2.2$ contributing $\rho_{\rm acc}^{\rm opt} = 0.8 \times 10^5 M_\odot/{\rm Mpc}^3$. Using the Boyle et al. (2000) LF, which is however inconsistent with high redshift data, $\rho_{\rm acc}^{\rm opt}$ increases by 20%. Thus the mass density accreted on BHs powering the optical QSO emission is a factor $\simeq 3$ lower than the estimated local SMBH mass density.

The estimate of $\rho_{\rm acc}^{\rm opt}$ is affected by uncertainties on $k_{\rm bol}^B$ and on ϵ. An upper limit of $k_{\rm bol}^B = 16$ can be derived from the Elvis et al. (1994) sample. On the other hand, recent data point to a lower bolometric correction than used in Eq. (10). For instance, McLure & Dunlop (2003) find $k_{\rm bol}^B \sim 8$, and Vestergaard (2003) finds $k_{\rm bol}^B = 9.7$ for higher redshift QSOs. On the whole we attribute to $k_{\rm bol}^B$ an uncertainty of about 30%. It is worth noticing that no dependence of the bolometric correction on optical luminosity has been reported.

The efficiency ϵ of conversion of accreted mass into outgoing photons can be as high as $\simeq 0.4$ for extreme-Kerr BHs. On the other hand, no firm lower limit to ϵ can be set; in extreme cases a BH can grow without radiating any photon at all. However, the low value of $\rho_{\rm acc}^{\rm opt}$ does not necessarily imply a low value of ϵ, since an additional important contribution to the local BH mass density is expected from highly absorbed hard X-ray selected AGNs, contributing a large fraction of the X-ray background energy density, but only marginally represented in optical surveys.

4.2 Mass accreted on X-ray selected AGNs

Recent data (see Hasinger 2003 for a review) have shown that a large fraction of the hard X-ray background is contributed by partially or completely covered AGNs in the luminosity range $\log(L_{2\text{-}10{\rm keV}}) = 42-44$ erg/s and at redshifts $z = 0.5$–1. A comprehensive study of the redshift-dependent hard X-ray AGN LF, including the distribution of the absorption column density N$_H$, has been recently carried out by Ueda et al. (2003; U03 from now on). In the following we will refer to their LDDE model, with the additional fraction of AGN with $24 < \log(N_H) < 25$ required in order to fit the XRB with the most recent normalizations (Vecchi et al. 1999; Barcons et al 2000; Gilli 2003). The additional AGN fraction implies an increase of the mass density by 25%.

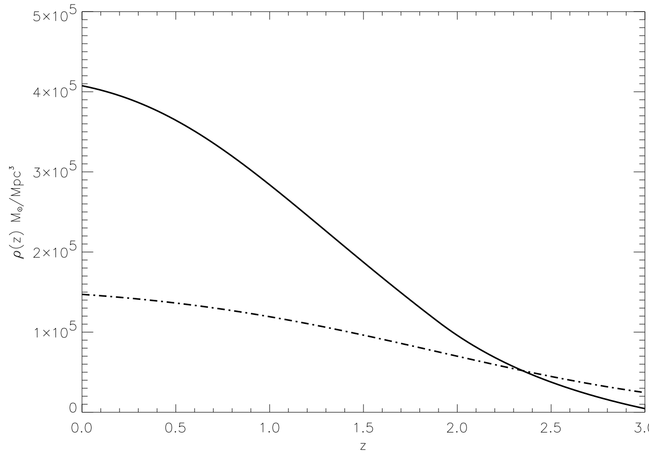

Figure 9. Accreted mass density as a function of redshift. The solid and the dot-dashed lines show the increase, with decreasing redshift, of the comoving accreted mass density as inferred from the epoch-dependent hard X-ray luminosity function by Ueda et al. (2003), with a luminosity dependent bolometric correction (see text), and from the optical luminosity function by Croom et al. (2003), respectively.

Unfortunately the available information on the overall spectral energy distribution of hard X-ray selected objects (and particularly of the faint ones, which are the most relevant to estimate the low mass end of the MF) is scanty, so that estimates of the bolometric corrections are difficult. The bolometric correction, $k_{\rm bol}^{2-10} \simeq 32$, derived by Elvis et al. (1994), refers to optically bright quasars. Evidences for an increase of the hard X-ray to optical luminosity ratio, $L_{HX}/L_{\rm opt}$ with decreasing optical luminosity have been reported by Vignali et al. (2003) and bolometric corrections, $k_{\rm bol}^{2-10} \simeq 12 - 18$, substantially smaller than the Elvis et al. (1994) value, have been estimated at least for a few Seyfert galaxies (Fabian 2003). Moreover, in order to match the optical LF of Boyle et al. (2000) starting from the hard X-ray LF, U03 had to assume that $L_{2\ keV} \propto L_{2500A}^{0.7}$ in close agreement with the observational data by Vignali et al. (2003).

The luminosity dependence of the X-ray to optical luminosity ratio does not necessarily imply a higher efficiency of low luminosity objects in producing X-ray (compared to optical) photons. An alternative explanation, borne out by evidences of larger covering factors for Seyfert galaxies compared to QSOs, is stronger dust extinction for lower luminosity objects which are less capable of pushing away the surrounding medium, as suggested long ago (Cheng et al. 1983).

If the optical/UV bolometric correction is independent of luminosity, the U03 relationship between UV and X-ray luminosity implies:

$$k_{\rm bol}^{2-10} = 17 \left(\frac{L_{2-10}}{10^{43} {\rm erg\,s^{-1}}} \right)^{0.43} . \tag{11}$$

Inserting Eq. (11) in Eq. (9), assuming $\epsilon/(1-\epsilon) = 0.1$, and integrating over the luminosity and redshift intervals ($41.5 \leqslant \log(L_{2-10{\rm keV}}) \leqslant 46.5$ and $z \leqslant 3$) investigated by Ueda et al. (2003), we find

$$\rho_{\rm acc}^{HX} \simeq 4.1 \times 10^5 M_\odot/{\rm Mpc}^3 \ . \tag{12}$$

If we extrapolate the LF up to $z = 6$, we get a mass density larger by 15%.

As a consistency check, we have subtracted the contribution of Type 2 AGNs, following the prescriptions given by U03, in order to get the contribution to the local mass density of Type 1 objects only. We find:

$$\rho_{\rm acc}^{\rm Type\,1} \simeq 1.5 \times 10^5 M_\odot/{\rm Mpc}^3 \ , \tag{13}$$

in close agreement with the result obtained using the optical LF [Eq. (10)]. The relatively large contribution of the optically selected AGNs to the local BH mass density ($> 30\%$), despite their small ($< 20\%$) contribution to the intensity of the HXRB, reflects their lower X-ray to optical luminosity ratio. Since $\rho_{\rm acc}^{\rm Type\,1} \propto [(1-\epsilon)/\epsilon]k_{\rm bol}^{2-10}$ and $\rho_{\rm acc}^{\rm opt} \propto [(1-\epsilon)/\epsilon]k_{\rm bol}^{B}$, from the agreement between the two estimates we can conclude that the uncertainty on $k_{\rm bol}^{2-10}$ is similar to that on $k_{\rm bol}^{B}$, i.e. $\simeq 30\%$.

The mass accretion history is illustrated by Fig. 9 showing the increase with decreasing redshift of the comoving accreted mass density, $\rho_{\rm acc}(z)$, as inferred from the optical (dot-dashed line) and from the hard X-ray (solid line) epoch dependent comoving luminosity function $n(L,z)$:

$$\rho_{\rm acc}(z) = \frac{1-\epsilon}{\epsilon c^2}\int_z^{z_{max}} dz' \frac{dt}{dz'} \int_{L_{min}}^{L_{max}} dL' \, k_{\rm bol} L' \, n(L', z), \tag{14}$$

where the X-ray (but not the optical) bolometric correction is a function of luminosity, as discussed above. As shown by Fig. 9, most of the accretion occurs at $z > 1.5$ for optically selected AGNs, and at $z < 1.5$ for hard X-ray selected AGNs.

The close correspondence of the accreted mass density inferred from the hard X-ray LF with the local SMBH mass density $\rho_{\rm BH} \simeq 4.2 \pm 1.0 \times 10^5 \, M_\odot/{\rm Mpc}^3$ (see Table 1) for $\epsilon/(1-\epsilon) = 0.1$ shows that *there is no much room for really "dark" accretion* (i.e. for accretion with radiative efficiency $\epsilon \ll 0.1$), confirming the findings by Salucci et al. (1999) and of Marconi et al. (2004), unless the luminous phases of the AGNs are characterized by radiative efficiencies much higher than the usually adopted value. But even if ϵ is close to the maximum allowed values ($\simeq 0.3$–0.4; Thorne 1974) the accreted mass accounts for $\geqslant 25$–30% of the local SMBH mass density, and one would be left with the problem of accounting for the correlations between $M_{\rm BH}$ and the bulge mass or velocity dispersion which arise naturally as a consequence of feedback associated to radiative accretion (Silk & Rees 1998; Cavaliere et al. 2002; King 2003; Granato et al. 2004).

A more explicit test of the role of accretion is obviously the comparison, presented in the next Section, of the resulting MF with the local SMBH MF.

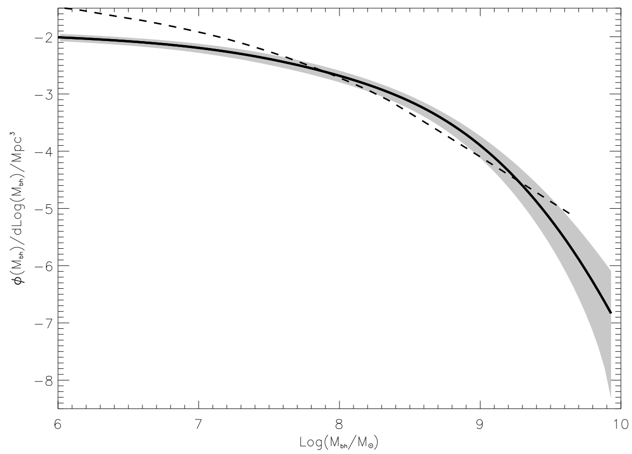

Figure 10. Local SMBH MF (solid line), including SMBHs hosted by both early- and late-type galaxies, with its 1σ uncertainty (shaded area), compared with the accreted MF (dashed line) estimated from the X-ray LF by U03, using a luminosity dependent bolometric correction. Such estimate is obtained by differentiating the integral mass function [Eq. (18)] with $\lambda = L/L_{\rm Edd} = 1$.

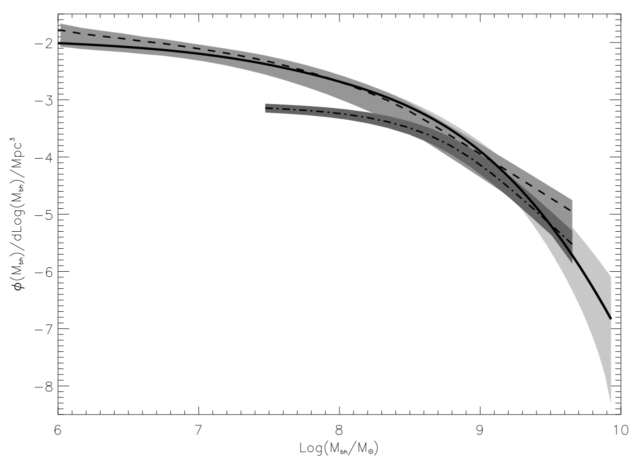

Figure 11. Comparison of the accreted MF (dashed line) computed as in Fig. 10, but for λ given by Eq. (19) with the local SMBH MF (solid line, with 1σ uncertainties represented by the shaded area). The dot-dashed line shows the accreted MF of optically selected QSOs ($M_B < -22.5$).

5 THE LOCAL ACCRETED MASS FUNCTION

The AMF can be derived from the AGN LF once a relationship between luminosity and BH mass is established (Chokshi & Turner 1992). Salucci et al. (1999) compared, under plausible assumptions, the accreted MF with the local SMBH MF to infer information on the accretion history. This point has been recently reexamined by a number of authors (e.g. Yu & Tremaine 2002; Aller & Richstone 2002; McLure & Dunlop 2003; Yu & Lu 2004; Marconi et al. 2004), who reached different conclusions.

Let us assume that the local SMBH mass is mostly due to radiative accretion and that the accretion rate $\dot{M}_{\rm BH}$ is proportional to $M_{\rm BH}$ (see e.g. Small & Blandford 1992; Cavaliere & Vittorini 2002; Marconi et al. 2004), at least during the main accretion phases. A recent analysis of SDSS quasars suggests that the two quantities are correlated (McLure & Dunlop 2003), although with a huge scatter, at least partly due to the uncertainties in BH mass estimates. An almost constant $\dot{M}_{\rm BH}/M_{\rm BH}$ is also expected, according to the phys-

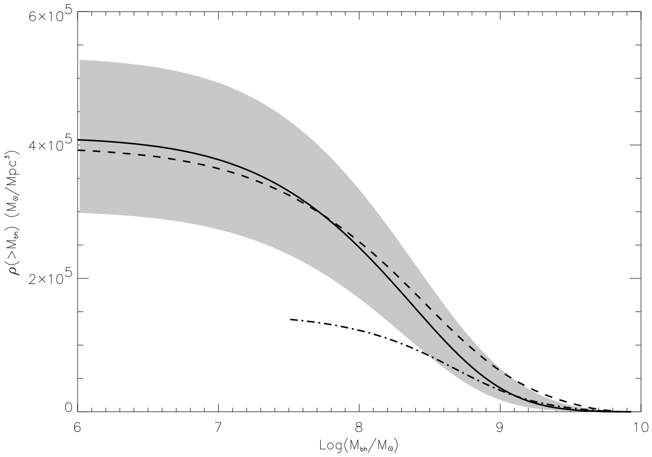

Figure 12. Cumulative local SMBH MF (dashed line) with its 1σ uncertainties, compared with the cumulative MF of optically selected QSOs ($M_B < -22.5$; dot-dashed line) plus X-ray selected Type 2 AGNs.

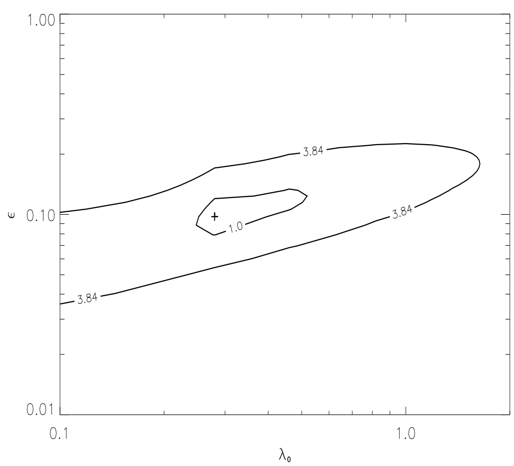

Figure 13. Iso-χ^2 contours in the ϵ–λ_0 plane for the match between the accreted and the local SMBH MFs. The contours are labelled with their value of $\Delta\chi^2$. The projections of the $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 3.84$ contours on the axis corresponding to a parameter give the 68% and 95% confidence intervals, respectively, for such parameter.

ical model of Granato et al (2004), during the fast growth of the SMBHs and up to the bright quasar phase.

If $\dot{M}_{\rm BH}/M_{\rm BH}$ is constant, the bolometric luminosity grows exponentially (as does the BH mass):

$$L_{\rm bol}(t) = \epsilon \dot{M}_{\rm acc} c^2 = \frac{\epsilon}{1-\epsilon}\dot{M}_{\rm BH} c^2 = \frac{\lambda c^2}{t_E} M_{\rm BH}(t_i) \exp\left[\frac{(t-t_i)}{t_{ef}}\right], \tag{15}$$

with e-folding time

$$t_{ef} = \frac{\epsilon t_E}{(1-\epsilon)\lambda}, \tag{16}$$

where λ is the average ratio $L/L_{\rm Edd}$, t_E is the Eddington time and t_i is the time when the growth starts. The e-folding time equals the Salpeter time if $\lambda = 1$.

The growth stops when the SMBH reaches its maximum mass, set equal to its present-day mass $M^0_{\rm BH}$, i.e. we neglect the mass increase during the declining phase of the light curve (see Yu & Lu 2004). The maximum bolometric luminosity is then:

$$L_{\rm bol,max}(M^0_{\rm BH}) = \lambda \frac{M^0_{\rm BH}}{t_E} c^2. \tag{17}$$

Under these assumptions, the local SMBH MF is related to the epoch-dependent LF in a given observational band by the energy balance equation:

$$\frac{1-\epsilon}{\epsilon c^2}\int_0^{t_0} dt \int_{\bar{L}}^{\infty} dL k_{\rm bol} L n(L,t) = \int_{\bar{M}^0_{\rm BH}}^{\infty} dM^0_{\rm BH} n(M^0_{\rm BH}) \left[M^0_{\rm BH} - \bar{M}^0_{\rm BH}\right], \tag{18}$$

where $\bar{L} = L_{\rm max}(\bar{M}^0_{\rm BH})$. The local MF $n(M^0_{\rm BH})$ is straightforwardly obtained differentiating Eq. (18) with respect to $\bar{M}^0_{\rm BH}$. It is worth noticing that the above equation can be also derived starting from the continuity equation (see e.g. Yu & Lu 2004).

In Fig. 10 the estimated AMF derived from the epoch-dependent X-ray LF by U03, assuming Eddington limited accretion ($\lambda = 1$), is compared with the local SMBH MF (including SMBHs hosted by both early- and late-type galaxies). Although the two curves are rather close to each other, their shapes differ. The fact that the assumption of Eddington limited accretion lead to an AMF exceeding the SMBH MF in some mass range shows that it cannot be true for all epochs and/or luminosities. Indeed, low-z/low luminosity AGNs are known to be radiating well below the Eddington limit (Wandel et al. 1999), and recent estimates suggest that quasars are in a sub-Eddington regime up to $z \simeq 2$ (McLure & Dunlop 2003; Vestergaard 2003).

The match between the AMF and the local SMBH MF indeed improves significantly (Fig. 11) if we adopt a redshift dependent Eddington ratio of the form:

$$\lambda(z) = \begin{cases} \lambda_0 & \text{if } z \geqslant 3 \\ \lambda_0[(1+z)/4]^\alpha & \text{if } z < 3 \end{cases}, \tag{19}$$

with $\lambda_0 = 1$ and $\alpha = 1.4$. The discrepancy at $M_{\rm BH} \geqslant 10^9$ $M_\odot$ is only marginally significant being at slightly more than 1σ level. On the other hand, the generally higher AMF estimate derived from the X-ray, compared to that from the optical, LF (see Fig. 11), reflects the strong luminosity dependence of the fraction of Type 2 AGNs, which are represented in the X-ray, but not in the optical, LF. X-ray surveys (see, e.g., Hasinger 2003) have shown that the Type 2 fraction increases from $\simeq 30\%$ at high luminosities ($L_{2-10\,\rm keV} \gtrsim 10^{44}\,\rm erg\,s^{-1}$) to $\simeq 70$–80% at low luminosities ($L_{2-10\,\rm keV} \lesssim 3\times10^{42}\,\rm erg\,s^{-1}$), consistent with the results of optical spectroscopic surveys of complete samples of nearby galaxies, without pre-selection (Huchra & Burg 1992; Ho et al. 1997). As a check, we have computed and plotted in Fig. 12 the cumulative accreted mass density function obtained summing the contribution of the optically selected QSOs to that of Type 2 X-ray selected AGNs; again, the

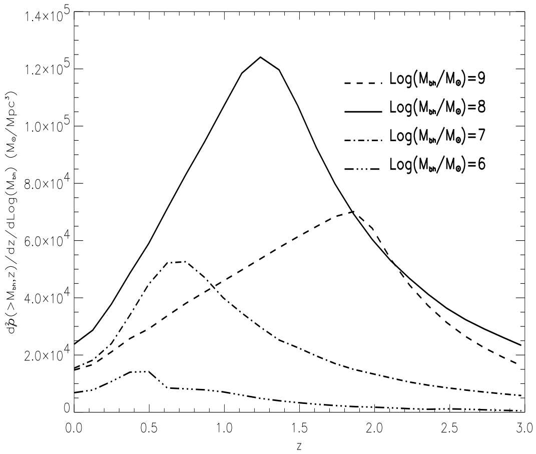

Figure 14. Contributions to the local SMBH MF as a function of redshift, for several values of $M^0_{\rm BH}$.

agreement with the local SMBH mass density function is very good.

We checked that a dependence of λ on luminosity, as suggested by Salucci et al. (1999), rather than on redshift, yields an equally good fit.

Requiring that the AMF matches the local SMBH MF we obtain constraints on the radiative efficiency and on the maximum value of the Eddington ratio [Eq. (19)]. A minimum χ^2 analysis yields $\epsilon \simeq 0.09\,(+0.04, -0.03)$ and $\lambda_0 \simeq 0.3\,(+0.3, -0.1)$ (68% confidence errors; see Fig. 13). The constraints on the parameter α ruling the evolution of the Eddington ratio [Eq. (19)] are rather loose ($0.3 \leqslant \alpha \leqslant 3.5$).

6 ACCRETION HISTORY AND AGN VISIBILITY TIMES

Replacing t_0 with t in Eq. (18) and differentiating with respect to z and $M^0_{\rm BH}$ we get the contributions to the $n(M^0_{\rm BH})$ from different cosmic epochs, shown for several values of $M^0_{\rm BH}$ in Fig. 14, which evidences that mass is accreted earlier and more rapidly by the more massive BHs.

The the mean time spent by an AGN at $L \geqslant \bar{L}$, averaged over the MF, writes:

$$\langle \tau_{\rm lum}(\bar{L}) \rangle = \frac{\int_0^{t_0} dt \int_{\bar{L}}^{\infty} dL n(L,t)}{\int_{\bar{M}^0_{\rm BH}}^{\infty} dM^0_{\rm BH} n(M^0_{\rm BH})}. \quad (20)$$

As noted by Yu & Tremaine (2002), $\langle \tau_{lum} \rangle$ is independent of ϵ. It depends however on $k_{\rm bol}$ and on λ since

$$\bar{L} = \frac{\lambda}{k_{\rm bol}} \frac{\bar{M}^0_{\rm BH}}{t_E} c^2. \quad (21)$$

Adopting the U03 LF, we find $\langle \tau_{\rm lum} \rangle \simeq 1.5 \times 10^8$ yr if we adopt a redshift-dependent Eddington ratio [Eq. (19)] and $\simeq 8 \times 10^7$ yr if we keep $\lambda = \lambda_0$.

This is however a lower limit to the time interval $\tau_{\rm vis}$, spent at $L \geqslant L_{\rm min}$, the minimum luminosity included in the LF. If $\dot{M}/M_{\rm BH} = $ const, the duration of the visible phase is simply:

$$\tau_{\rm vis}(M^0_{\rm BH}) = t_{ef} \ln\left[\frac{L_{\rm max}(M^0_{\rm BH})}{L_{\rm min}}\right] = t_{ef} \ln\left[\frac{M^0_{\rm BH}}{M^{\rm min}_{\rm BH}}\right], \quad (22)$$

where $M^{\rm min}_{\rm BH}$ is the BH mass when radiative accretion yields luminosity $L \geqslant L_{\rm min}$. In the case of the X-ray LF of U03, the minimum 2–10 keV luminosity included at $z \simeq 0.8$, where the contribution to the X-ray background peaks, is $\log(L_{\rm min}) \simeq 42$–$42.4$. With the bolometric correction given by Eq. (11), the corresponding minimum BH mass is:

$$M^{\rm min}_{\rm BH} = \frac{5 \times 10^4}{\lambda} \frac{L_{\rm min}}{10^{42} {\rm erg\,s^{-1}}} M_\odot. \quad (23)$$

The minimum BH mass contributing to the LF of optically selected QSOs for the bolometric correction by Elvis et al. (1994) is :

$$M^{\rm min}_{\rm BH} = \frac{3 \times 10^7}{\lambda} 10^{-0.4(22.5 + M_B^{\rm max})} M_\odot, \quad (24)$$

where $M_B^{\rm max} \simeq -22.5$ (Boyle et al. 2000; Croom et al. 2003).

The condition that the AGN visibility timescales determined via the LF and via the local SMBH mass function are equal:

$$\int_0^{t_0} dt \int_{\bar{L}}^{\infty} dL n(L,t) = t_{ef} \int_{\bar{M}^0_{\rm BH}}^{\infty} dM^0_{\rm BH} n(M^0_{\rm BH}) \ln(\frac{M^0_{\rm BH}}{\bar{M}^0_{\rm BH}}), \quad (25)$$

add further constraints on ϵ and λ_0. Using the U03 LF and assuming a 30% uncertainty on the bolometric correction for X-ray luminosities, we find an allowed range for ϵ pretty similar to that following from the match between the AMF and the local SMBH mass function ($0.06 \leqslant \epsilon \leqslant 0.13$) while the constraints on the Eddington ratio are looser ($0.5 \leqslant \lambda_0 \leqslant 2$).

7 DISCUSSION AND CONCLUSIONS

The analysis reported in the first part of the paper shows that the local mass function of SMBHs can be rather accurately assessed. More in detail, the MF of SMBHs hosted in early-type galaxies can be obtained exploiting the velocity dispersion or luminosity functions of host galaxies, coupled with the $M_{\rm BH}$–σ or $M_{\rm BH}$–$L_{\rm sph}$ relationships, respectively. The results obtained in the two ways are in remarkable agreement with small uncertainties up to $M_{\rm BH} \geqslant 10^9 M_\odot$ (cfr. Fig. 7). The contribution from SMBHs hosted by late-type galaxies is more uncertain, and is mostly confined to the low mass end of the MF.

The overall SMBH mass density amounts to $\rho^0_{\rm BH} = (4.2 \pm 1.1) \times 10^5 M_\odot/{\rm Mpc}^3$, with a contribution from SMBHs in late-type galaxies of $\simeq 25\%$. This value of $\rho^0_{\rm BH}$ is higher than those found by Yu & Tremaine (2002), by Aller & Richstone (2002) and by McLure & Dunlop (2003) (who have not considered the contribution from SMBH residing in late type galaxies), but is in excellent agreement with the results by Marconi et al. (2004). The local number density of the SMBHs more massive than $10^6 M_\odot$ is $n(M^0_{\rm BH} > 10^6\ M_\odot) \simeq 1.7 \times 10^{-2}\,{\rm Mpc}^{-3}$, which corresponds to the number of bulges and spheroids with $M_{\rm sph} > 5 \times 10^8$ $M_\odot$.

The Soltan (1982) argument applied to the hard X-ray

selected AGNs, allowing for a luminosity-dependent bolometric correction (U03; Fabian 2003), yields, for a mass to radiation conversion efficiency $\epsilon = 0.1$, an accreted mass density of $\rho_{\rm acc}^{HX} \simeq 4.1 \times 10^5 M_\odot/{\rm Mpc}^3$, in close agreement with the local SMBH mass density, indicating that most of the BH masses were accumulated by radiative accretion, as previously concluded by Salucci et al. (1999). Optically selected QSOs account for only $\simeq 35\%$ of the total SMBH mass density. The dominant contribution comes from Type 2 AGNs, mostly missed by optical surveys.

Not only the mass density, but also the MFs of the SMBHs and of the accreted mass match remarkably well, if we allow for a decrease of the Eddington ratio $\lambda = L/L_{\rm Edd}$ with redshift [Eq. (19)], as suggested by observations (McLure & Dunlop 2003; Vestergaard 2003). Optically selected, Type 1 AGNs account for the high mass tail of the AMF, while Type 2 AGNs take over at lower masses, reflecting the strong increase with decreasing luminosity of the Type 2 to Type 1 ratio demonstrated by hard X-ray surveys (see, e.g., Hasinger 2003) and consistent with the outcome of spectroscopic surveys of complete samples of nearby galaxies, without pre-selection (Huchra & Burg 1992; Ho et al. 1997).

The alternative possibility that most of the mass has been accumulated by "dark" accretion (i.e. accretion undetectable by either optical or hard X-ray surveys, as in the case of BH coalescence), is severely constrained by the above results. In order to make room for this possibility one has to assume that the radiative efficiency during the visible AGN phases is at the theoretical maximum of $\epsilon \simeq 0.3$–0.4. But even in this case (unless the bolometric correction is far lower than currently estimated) the contribution of radiative accretion to the local SMBH mass density is $\gtrsim 25\%$, and one is left with the problem of fine tuning the radiative and non-radiative contributions in order not to break down the match with the local SMBH MF obtained with radiative accretion alone. One would also face the problem of accounting for the tight relationships between BH mass and mass or velocity dispersion of the spheroidal host, naturally explained by feedback associated to radiative accretion. For these reasons it is unlikely that the present day SMBH mass function has been built *mostly* through 'dark' accretion or merging of BHs.

If indeed the SMBH MF has to be accounted for by radiative accretion, the requirement that it fits together with the AMF constrains the radiative efficiency and the maximum Eddington ratio to $\epsilon \simeq 0.09\,(+0.04, -0.03)$ and $\lambda_0 \simeq 0.3\,(+0.3, -0.1)$ (68% confidence errors). The condition that the mean AGN visibility timescale computed via the LF and via the local MF are equal [Eq. (25)] yields an allowed range for ϵ very close to the above ($0.06 \leqslant \epsilon \leqslant 0.13$) and looser (but consistent) constraints on λ_0.

The analysis of the accretion history highlights that the most massive BHs (associated to bright optical QSOs) accreted their mass faster and at higher redshifts (typically at $z > 1.5$), while the lower mass BHs responsible for most of the hard X-ray background have mostly grown at $z < 1.5$ (see Figs. 9 and 14). The different evolutionary behaviour of the two AGN populations can be understood if gas accretion is regulated by star formation and by feedback both from supernova explosions and nuclear activity (e.g. Kawakatu & Umemura 2003; Granato et al. 2004). In this framework it is expected that the hosts of the most massive BHs have the oldest stellar populations (Cattaneo & Bernardi 2003).

The mass-weighted duration of the luminous AGN phase is found to be $\langle \tau_{\rm lum} \rangle \simeq 0.5$–$1.5 \times 10^8$ yr. Yu & Tremaine (2002), using a similar method, got slightly lower values, because they used in Eq. (20) the optical QSO LF and the local MF of SMBHs in early-type galaxies, which, as shown in Sect. 3, is only partly accounted for by optically selected QSOs. Yu & Lu (2004), from a detailed modelling the luminosity evolution of individual QSOs, derived a lower limit $\tau_{\rm lum} \geqslant 4 \times 10^7$ yr.

If the accretion rate per unit BH mass, $\dot{M}_{\rm BH}/M_{\rm BH}$, is constant (as in the case of Eddington limited accretion) during the main accretion phases, the visibility times increase with BH mass [Eq. (22)], consistent with the finding by McLure & Dunlop (2003) that the ratio of SMBH in their optically selected sample at $z \simeq 2$ to the corresponding number density at the present day increases with BH mass. These authors estimate, for the most massive BHs ($M_{\rm BH} \geqslant 10^{9.5}\,M_\odot$), a lower limit to $\tau_{\rm vis}$ (lifetime in their terminology) of 10^8 yr.

Setting $\lambda = 1$ and $\epsilon/(1-\epsilon) = 0.1$ and inserting in Eq. (22) the value of $\bar{M}_{\rm BH}$ given by Eq. (24) with $M_B = -22.5$, we get $\tau_{\rm vis}(10^{9.3}\,M_\odot) \simeq 2 \times 10^8$ yr. Inserting instead in Eq. (22) the value of $\bar{M}_{\rm BH}$ given by Eq. (23) with $\log(L) = 42$ we get $\tau_{\rm vis}(10^6\,M_\odot) \simeq 1.2 \times 10^8$ yr, $\tau_{\rm vis}(10^8\,M_\odot) \simeq 3 \times 10^8$ yr and $\tau_{\rm vis}(10^{9.3}\,M_\odot) \simeq 4.4 \times 10^8$ yr. Such visibility times increase with decreasing redshift for $z < 3$ [Eq. (19)].

On the contrary, Marconi et al. (2004) infer mean "lifetimes" increasing with decreasing present day BH masses. For $\lambda = 1$ and $\epsilon = 0.1$ they get $\sim 1.5 \times 10^8$ yr for $M_{\rm BH}^0 > 10^9\,M_\odot$ and $\sim 4.5 \times 10^8$ yr for $M_{\rm BH}^0 < 10^8\,M_\odot$. However, the latter "lifetime" corresponds to $\simeq 11$ e-folding times, i.e. to a mass increase by a factor 4.5×10^4. But then for a large fraction of their "lifetime" low mass BHs are too faint to be included in actual LFs [cf. Eq. (23) and Eq. (24)].

In this context we also note that the amount of time spent above the threshold for inclusion in the LF by objects reaching large luminosities/masses cannot be constrained by the LFs themselves since such objects are too rare to contribute significantly to the faint end of the LF.

Our estimates for $\tau_{\rm vis}$ are within the broad constraints imposed on one side by the QSO evolution timescale ($<$ 1 Gyr) and on the other side by the proximity effect ($>$ 10^4 yr; see Martini 2004). The low "lifetimes" inferred (although with large uncertainties) from clustering properties of optical QSOs (Martini & Weinberg 2001; Martini 2004) depend basically on the crude assumption that as soon as a massive halo virializes, the QSO appears, without any delay.

Short visibility times ($\tau_{\rm vis} \leqslant 0.02$ Gyr) are also implied by the models of QSO LFs presented by Haehnelt, Natarajan & Rees (1998), and Wyithe & Loeb (2003). However, Hosokawa (2002) has shown that, in the same general framework, the QSO LF can be reproduced with substantially higher values of $\tau_{\rm vis}$. Again, short timescales mainly follow from the assumption of immediate QSO ignition at the virialization of the host DM halo. As shown and discussed by Monaco et al. (2000) and Granato et al. (2001), a delay between virialization and AGN ignition is a key ingredient to understand the QSO LF and the relationship between evolutionary histories of QSOs and of the massive spheroidal galaxies hosting them. Granato et al. (2004) have presented

a detailed physical model quantifying such delay and its increase with decreasing mass.

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